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DEVELOPMENT OF INSTRUMENTATION TO MONITOR RADIAL DEFORMATION OF THE MEDIUM AROUND AN UNDERGROUND OPENING

D. E. Rasmussen

Battelle Memorial Institute

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Development of Instrumentation to Monitor the Radial Deformation of the Medium Around an Underground Opening

Semiannual Technical Report
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The objectives of ~~this~~ research and development program are to develop two unique types of instrumentation suitable for measuring deflection of the medium surrounding an underground opening. The two instrument systems being developed are referred to as the "Self-Contained System" and the "Laser System". ~~This~~ report covers work performed on both systems during the first-half of the second contract year. During the first contract year, ~~we completed~~ concept selection, component evaluation, and prototype design and fabrication for the Self-Contained System and concept selection and component evaluation for the Laser System. During the first half of the current contract year, we have completed laboratory and field evaluation of the Self-Contained System and ~~have~~ design, fabrication and component evaluation of the Laser System well underway.

Details of illustrations in this document may be better studied on microfiche.

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INTRODUCTION

The objectives of this research and development program are to develop two unique types of instrumentation suitable for measuring deflection of the medium surrounding an underground opening. The two instrument systems being developed are referred to as the "Self-Contained System" and the "Laser System".

We are midway through the second year of a planned three-year research and development effort. Work performed during the first year is reported in the semiannual and annual technical reports dated August 30, 1971 and March 9, 1972, respectively. This report covers work performed on both systems during the first-half of the second contract year. The report includes a summary of work accomplished, followed by detailed technical discussions presented in two major sections entitled Self-Contained System and Laser System.

SUMMARY

During the first contract year, we completed concept selection, component evaluation, and prototype design and fabrication for the Self-Contained System and concept selection and component evaluation for the Laser System. During the first half of the current contract year, we have completed laboratory and field evaluation of the Self-Contained System and have design, fabrication, and component evaluation of the Laser System well underway.

THE SELF-CONTAINED SYSTEM

Final assembly of all components into the prototype instrument was completed and laboratory evaluations planned for this prototype were detailed. Four distinct steps in the laboratory evaluation were completed:

1. The assembled prototype was set up on a laboratory bench and operated for three days,
2. The assembled prototype was installed in an environmental chamber, where conditions expected underground were simulated, and operated for seven days,
3. The assembled prototype was immersed in a trough of water and operated for seven days,
4. The assembled prototype was installed in a facility where its tolerance to blast-induced shock could be evaluated.

The prototype instrument survived each of these laboratory tests in a very satisfactory manner.

Concurrent with the laboratory evaluation of the prototype, we conducted a series of tests on the anchor system planned for use with the prototype underground. Based on the results of these tests, an anchoring system evolved which we felt had a good chance of successful operation underground. During the later part of this reporting period, plans for the underground prototype evaluation were finalized and actual underground work was completed during the last month. Although we had an electronic failure during one of the underground tests, we consider the underground evaluation to have been completed successfully since the electronic failure was not caused by the underground environment. We did have difficulties with the anchoring system originally planned (due mostly to gross irregularity of the bore holes) and continued to modify the anchoring system throughout the test series.

LASER SYSTEM

Work during the first six months has been directed toward finalization of conceptual design, detailed mechanical and optical design of prototype components, and fabrication and procurement of items necessary for assembly of the prototype system. Assembly is currently underway.

Development work conducted during this period has verified the basic concept selected for monitoring the relative motion of targets mounted in tunnel walls and has provided the basis for design decisions which resulted in changes in certain components of the instrument from those adopted during the previous contract year. Significant changes include:

- Transition from a two-frequency spatial modulation system to a single frequency approach using time gating for identification of the two directions of motion of the target in the beam.
- Development of a two-directional cylindrical single-frequency modulator, or chopper. Mirrors are used instead of prisms to achieve both vertical and horizontal modulation on the beam.
- Incorporation of a worm-wheel set as one element of the beam scanner, enabling the device to be useful for scanning both directions down a tunnel.

SELF-CONTAINED INSTRUMENT FOR THE U.S. BUREAU OF MINES

During the last month of the first contract year, the individual components of the self-contained instrument prototype were completed and readied for permanent assembly as a unit. These components included the complete battery pack and connectors, the light emitting diode/photo transistor package which was "O" ring sealed in one of the containment tube end closures, the solenoid driver boards for the punch pin selector, the prototype electronic package, and the containment tube and end-fittings. The prototype instrument components were permanently assembled (see Figure 1) and operational testing and debugging was started.

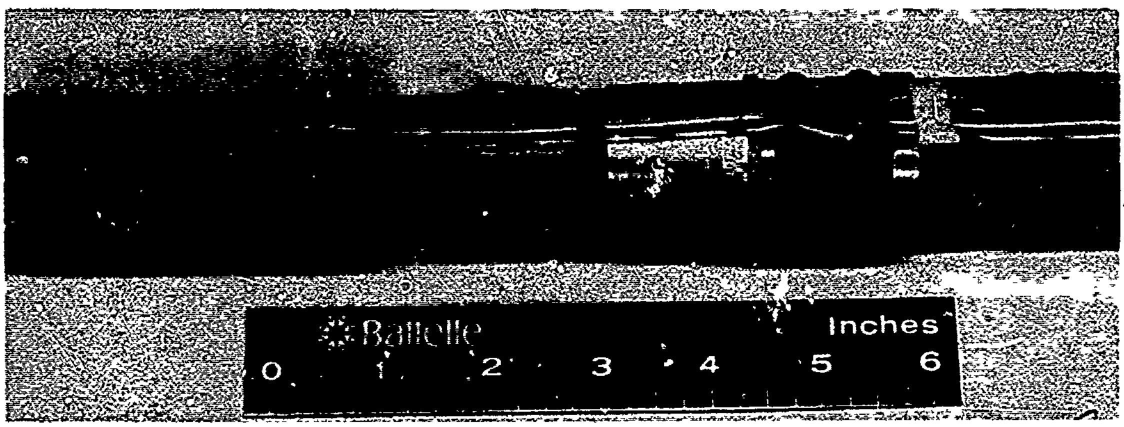

FIGURE 1. Closeup of Prototype Self-Contained Instrument Showing Electronic Circuit Boards Connected to the Punched Paper Tape Recorder

LABORATORY EVALUATION

To start the current contract year, we continued evaluation of the prototype instrument and leak-tested the containment tube with the end fittings in place. With this completed, the assembled instrument components were inserted into the containment tube and mounted on a test jig which incorporated a micrometer slide adjustment for the Linear Variable Differential Transformer (LVDT) core (Figure 2). The system was operated

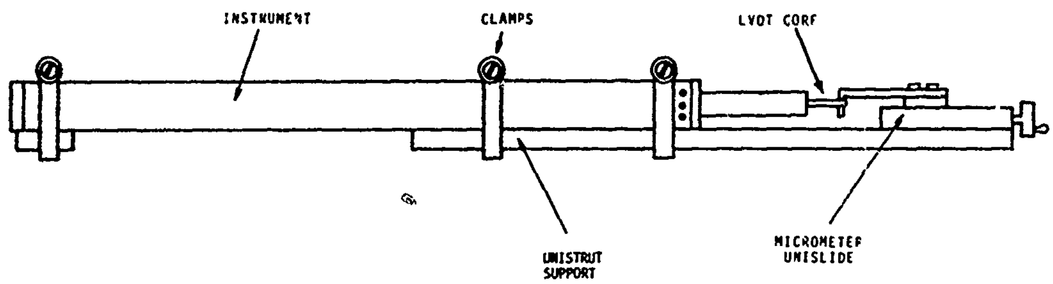

FIGURE 2. Test Jig Used for Laboratory Evaluation

at room temperature for 72 hr in the automatic mode with a measuring frequency of 1000 sec. The LVDT core was re-positioned over its 3-in. travel (at intervals of 0.250 in.) throughout the 72 hr run. Although the results of this run were satisfactory, the data collected indicated that the instrument zero point was misplaced and a small amount of linearity error existed. Battery voltages after the run showed ample supply for longer test runs. This was the first time the prototype had been operated self-contained for a typical period of time.

Following this initial laboratory test, changes were made in the electronics in order to shift the instrument zero and improve the overall linearity of the instrument. Subsequent linearity checks on the electronics showed a small attenuation of the signal at the extreme ends of the 3-in. core travel. This is a fault of the LVDT design and probably can be corrected if eventually necessary.

The next laboratory test for the prototype was designed to determine its ability to withstand simulated mine environment. The prototype was installed, with the previously used test jig, into the environmental chamber. It was operated self-contained for seven days with a data recording frequency of 1000 sec. Again, the micrometer slide was used

to re-position the LVDT core in intervals of 0.250 in. throughout the test period. Visual readings were taken after each movement of the LVDT case. Conditions maintained in the chamber during the test included:

- Air velocity — 2.3 mph
- Humidity — 95 to 100%
- Temperature — Normally at 120°F but allowed to decay to room temperature over a weekend
- pH — 7.1

Inspection of the instrument after removal from the chamber and containment tube showed no signs of moisture, and the punched tape was in very good condition with no damage. The battery pack was in good condition with enough reserve capacity for further operation.

An error of 0.135 in. was recorded in both the visual readout and the punch tape during the temperature change from 75 to 119°F. A temperature drift study was conducted on the entire instrument to determine the area that was temperature sensitive and it was found to be in the LVDT. This problem was discussed with the manufacturer. Additional drift studies were conducted at a later date and are discussed later in this report.

The instrument was prepared for a second seven-day test. This run was to be done with the instrument totally submerged in a tank of water at temperatures of 60 to 71°F (room temperature). Examination of the instrument after removal from the submerged water test again showed no signs of moisture inside of the instrument and the paper tape was in very good condition; however, a malfunction of the recorder paper tape advance rachets occurred approximately 75 hr after the start of the test. The rachets were cleaned, lubricated and readjusted and subsequently worked satisfactorily.

The complete system, including the self-contained instrument and both the deep anchor and the adjustable (shallow) anchor, was installed in a 2 in. ID lucite tube for demonstration purposes. Subsequent to the demonstration it was set up in the environmental chamber in order to study the specific error introduced by temperature change. The temperature in the chamber was stabilized a minimum of 2 hr before each set of readings

were taken. At each temperature level, the core of the LVDT was moved from 0 to 3 in. in increments of 0.250 in. A visual readout was taken at each setting of the LVDT core. During the 121°F temperature check, the instrument stopped operating. The trouble was traced to an electronic component failure. Although it is likely this failure resulted from the elevated temperatures, it probably was caused by aggravation, by temperature, of a flaw in the electronic component. The results of this study are shown on the graph of core setting versus instrument readout, Figure 3.

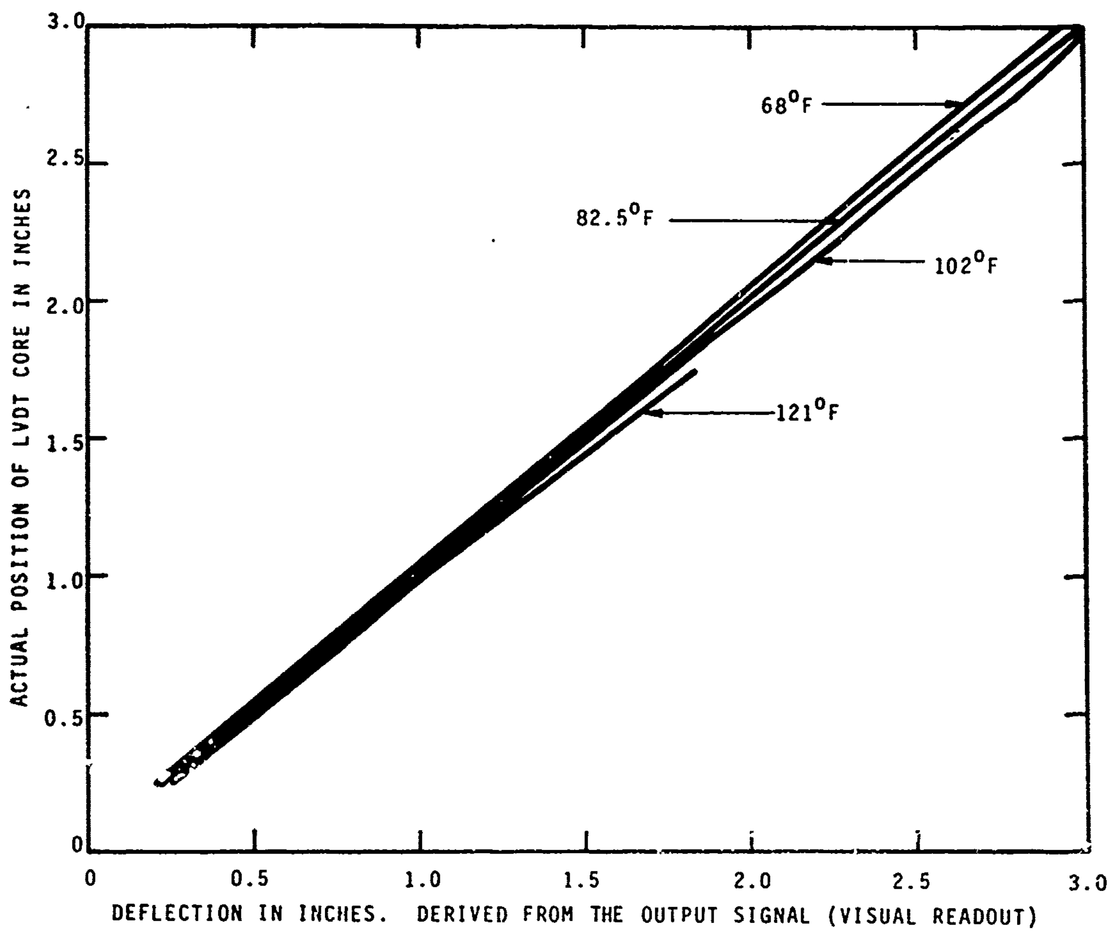

FIGURE 3. Temperature Introduced Error of the Self-Contained Instrument

Next, a test was conducted to evaluate the shock and vibration tolerance of the instrument. As shown in Figure 4, the instrument was installed in a reinforced concrete block using the adjustable anchor arrangement. The 12 in. by 12 in. by 6 in. concrete block consisted of Type III cement (high early) 7 day, 1/4 in. minus concrete sand reinforced with 0.016 in. by 3/4 in. Wirand® and had a 2 in. hole through the center to simulate a bore hole. Two accelerometer pads were embedded into the cement, one on the side 1 in. from the 2 in. anchor hole and one embedded in the top of the block. The cement block was grouted into place on a cement floor and against a cement wall. The adjustable anchor shell was fastened into the 2 in. hole and the complete adjustable anchor installed along with the self-contained instrument. The deep end of the instrument was supported by the LVDT core. The concrete block was subjected to controlled impacts. A 12 lb sledge swinging at a 12 in. radius striking the side of the block (see Figure 5) was used to create the shock. Two accelerometer mounts were used for pickup; one on the side of the block and the second one mounted on the instrument over the LED package. Shock was measured on both the concrete block and the instrument. The block registered accelerations of 100 G at 6 kHz, while the instrument experienced about 3 G acceleration. The impact loading was increased to 506 G with about 6 G acceleration transferred to the instrument. Throughout the entire test the instrument operated satisfactorily.

Further study of the temperature drift problem was conducted on LVDT serial No. 5. The LVDT and a micrometer slide were attached to a short section of unistrut as shown in Figure 6. The core of the LVDT was then attached to the movable section of the slide. The LVDT was positioned in a heater. A Variac was used to control the heater voltage. The output leads of LVDT were attached to a 25 KΩ load. The output voltage was read out on a differential volt meter. Results of this test indicated a temperature error of more than 20% of full range per 100°F. The test results were forwarded to the LVDT vendor for evaluation.

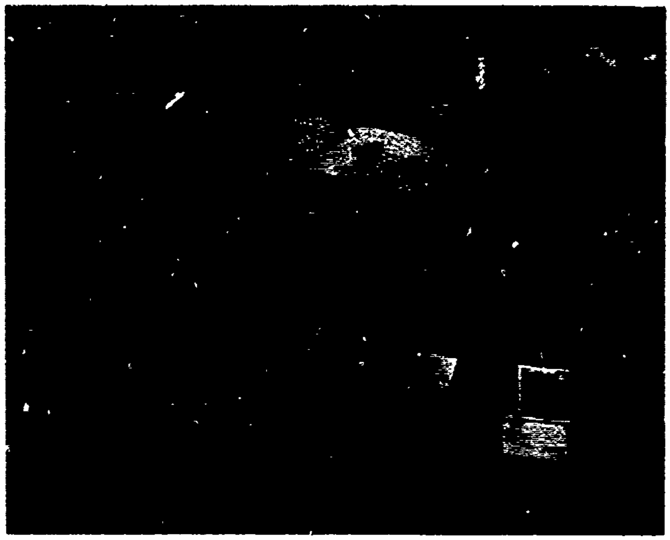

FIGURE 4. Experimental Test Setup Used to Establish the Self-Contained System's Tolerance to Shock

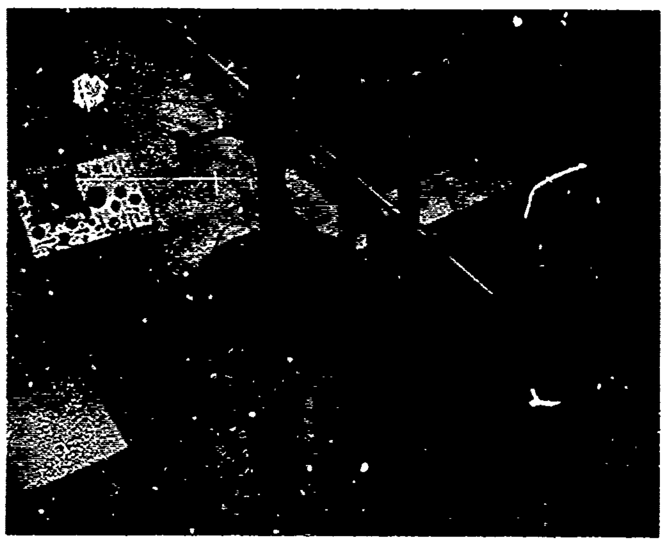

FIGURE 5. Another View of Shock Tolerance Test Setup Showing Sledge and Accelerometer

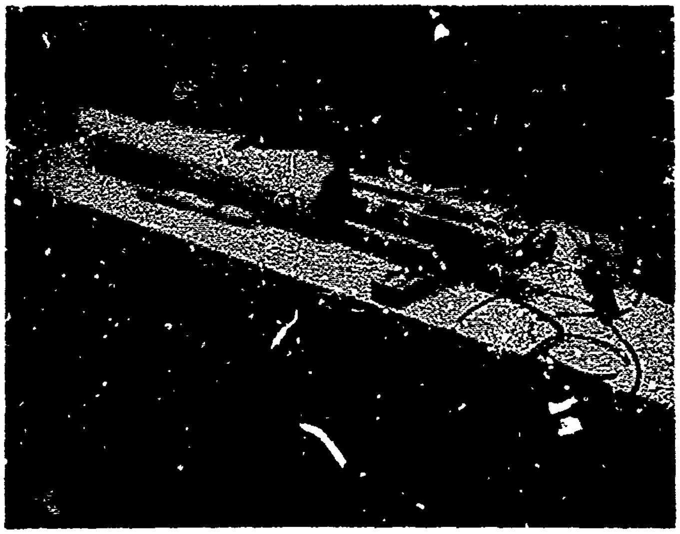

FIGURE 6. Arrangement Used to Determine Temperature-Induced Air in the LVDT; Shown are Micrometer Slide and Heater Assembly with LVDT Installed

Concurrent with the instrument laboratory evaluation described above, we conducted a series of laboratory and field evaluations on the anchor concepts we had selected. These were performed to establish feasibility of the concept and to select the grouting material to be used.

Requirements for the deep anchor prompted us to build a 4 in. by 2 in. solid aluminum cylinder with external ribs, to which a thin glass ball was glued. The ball was filled with an adhesive, slipped into a test hole and crushed, thus forcing the adhesive around the anchor. This method was discontinued because of the difficulty encountered in injecting the adhesive into the ball and the fragility of the ball itself.

Using the same anchor, we attached the lid of a salmon egg jar to the anchor, mixed the adhesive in the jar, attached the jar to the lid and inserted the entire assembly into a test hole. Considerable force was needed to crush the jar. The glass was too thick and only about one-fourth of the anchor was covered by adhesive.

The third method was more successful. We bored the 4 in. aluminum anchor 3 in. deep by 1-1/2 in. ID. A piston was made to fit. Six 1/4 in. holes were drilled in the anchor to let the adhesive extrude through. We mixed the adhesive in a separate container and poured it into the anchor. We then installed the piston and held it in place with 1/8 in. wooden dowels. The assembly was inserted into the test hole. When the anchor assembly reached the bottom of the hole, a sharp rap sheared the wooden dowels and a steady pressure forced the piston into the anchor extruding the adhesive out of the holes and around the anchor (see Figure 7). This method appeared satisfactory except for the cost to fabricate. Using this concept, we put together an anchor using pipe fittings, resulting in a major cost reduction.

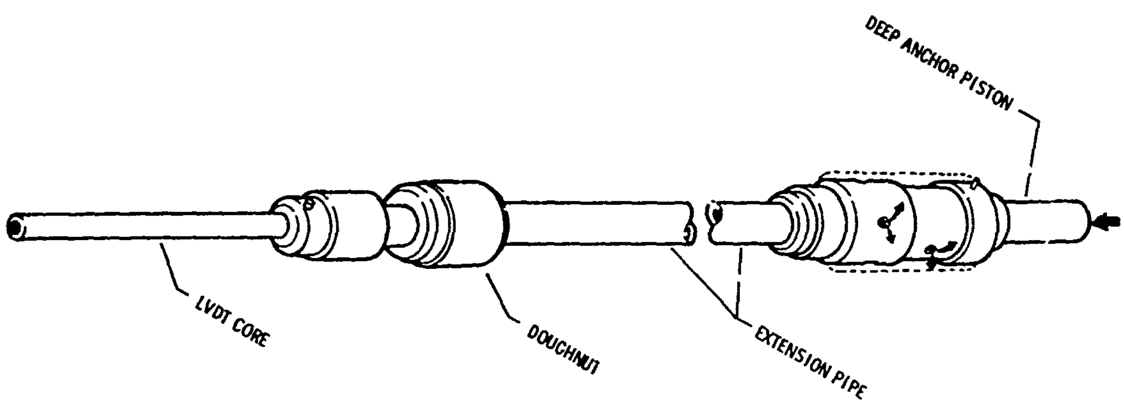

FIGURE 7. Schematic of Deep Anchor with Extension Pipe

The shallow anchor (Figure 8) is a 2 in. externally ribbed cylinder, 3-1/2 in. long, 1.660 in. ID with 1 in. of 1-3/4-12 UNC internal thread at one end. Adhesive is extruded from the inside out using a special tool. This tool is a two-part item, one part having an internal and an external thread. This external thread accepts the anchor. The second part has an external thread that screws into and through the internal thread of the first part.

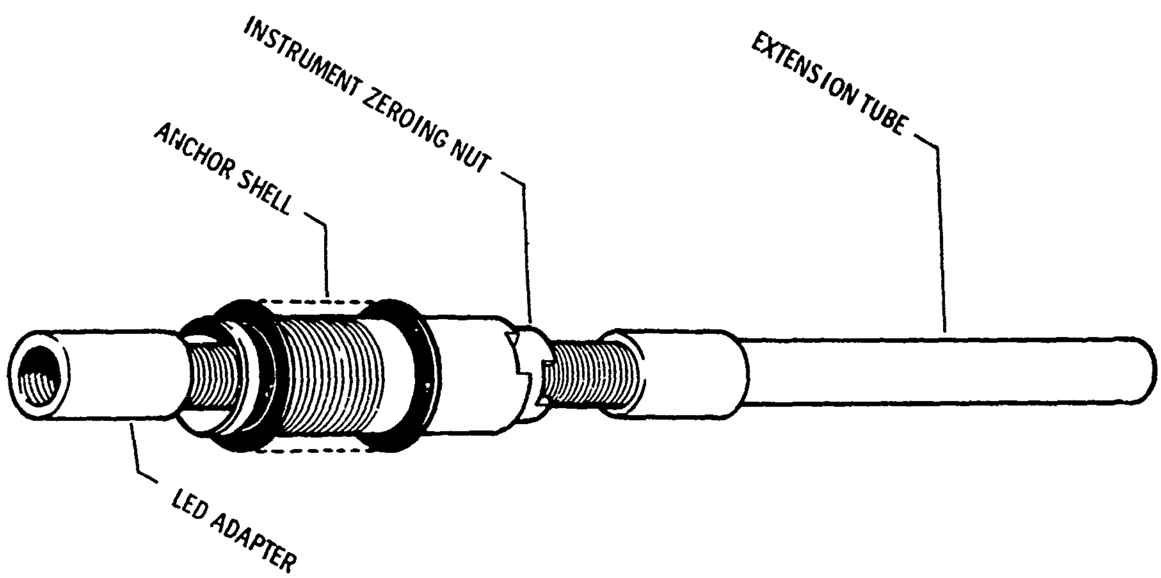

FIGURE 8. Schematic of Shallow Anchor Assembly

During installation the anchor is assembled on a 1-3/4 in. thread (part of the installation tool) and a seal slips in the anchor and bottoms on the end of this threaded portion. Two 1/8 in. holes are drilled in the anchor at the lip of this seal. The internal shaft is threaded into and through the anchor holding tool. This shaft has 2-3/4 in. of smooth surface that will slip through the seal that was installed in the

anchor. The adhesive is poured into the anchor and around the internal shaft. With the anchor full of adhesive, a second seal is installed over the internal shaft and a backup collar set-screwed to the shaft. We now insert the anchor and tool into the hole to a desired depth. By turning the internal shaft counter clockwise, we pull the seals together extruding the adhesive through the two 1/8 in. holes and around the outside of the anchor. The tool is wedged in place until the adhesive has cured. After a suitable time for curing, the tool and seals can be removed leaving the anchor bonded to the wall of the hole.

Laboratory tests were performed on both the deep and shallow anchors, but a suitable adhesive and a means of testing the adhesive with the anchors was needed. A deep and shallow anchor pull test stand was built using an automotive stand, a 1.5 ton hydraulic jack and a Dillon tension gage (see Figure 9). As shown in Figure 10, a 4 ft by 3-1/2 ft by 3 ft nonporous boulder was located and five 2 in. and five 2-1/4 in. holes were drilled to depths of approximately 10 in. Five adhesives were tested: Hysol epoxy, Roc-Loc, water plug, furnace epoxy and Por-Rok. These adhesives were tested in dry, damp and wet holes. In our tests Por-Rok performed the best. It is easy to work, can be mixed to varied viscosities with the same final results and water is all that is needed. The anchor pull test stand worked very well and was capable of pulling 3000 lb in the vertical or horizontal position (Figure 11).

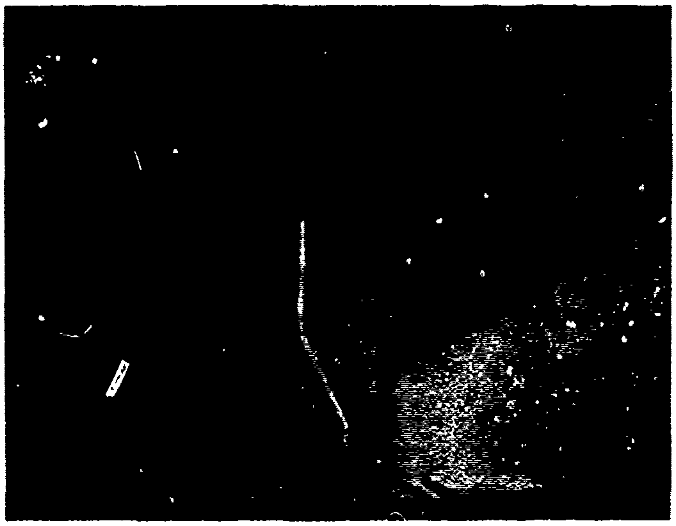

FIGURE 9. Anchor Pull Test Stand

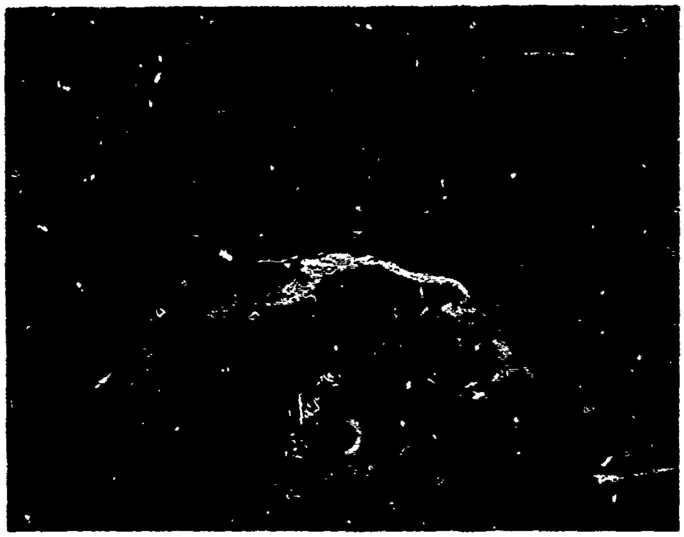

FIGURE 10. Boulder Used for Testing Both Shallow and Deep Anchors

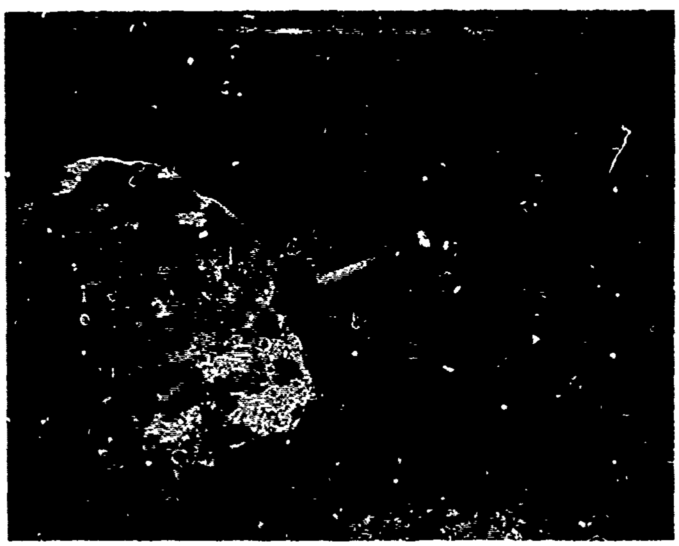

FIGURE 11. Anchor Test Stand Being Used During Anchor Evaluation

FIELD EVALUATION

After completion of laboratory evaluation, we prepared for underground evaluation of the self-contained instrument system. This consisted of two basic steps. First, we needed to arrange a site for the evaluation and second, we needed to complete preparation of the instrument system and installation equipment. A meeting was held with U.S. Bureau of Mines personnel and Hecla Mining Company personnel at Burke, Idaho and details were worked out for the evaluation. Start of the test series was planned for the 27th of July. Mining company personnel would drill the holes and provide one man to advise us during installation and removal of the instrument. The U.S. Bureau of Mines planned on having one or two people present during the installation and removal of the instrument system; we would normally furnish a two-man team during installation and one man during removal of the system. Before the start of underground evaluation, the Lucky Friday Mine at Mullen, Idaho was selected as the test site.

The other step needed before start of underground testing was final preparation of the instrument system and installation tools. The instrument was assembled and all of the specified tools were collected in the laboratory and checked out for each of the operations. General hand tools and materials needed for installation, such as polyester resin, brushes, tape, and Por-Rok were obtained. The entire instrument system was installed in a piece of thick wall cardboard tube used to simulate the borehole. This final check was done to evaluate operability of the installation tools and to check our planned installation procedure. This entire laboratory dry run worked out satisfactorily. The instrument was disassembled, the batteries recharged, and a new paper tape installed in preparation for the first underground test.

All equipment was moved to the Lucky Friday Mine and taken underground. The test site to be used was located at the 4050 level in a nearly horizontal borehole drilled about 25 ft from the working face of a drift. During installation we encountered two major problems. First, the borehole was much more crooked than we had anticipated and second, the first 14 ft of

the borehole was 2-1/4 in. in diameter rather than 2 in. as we had planned. Neither problem caused any difficulty in installing the deep anchor, but the oversize hole required that we modify the shallow anchor so that the Por-Rok would stay in place. We did this by wrapping several layers of tape around the tunnel end of the shallow anchor so that the Por-Rok would not run out when it was extruded. The oversize nature of the hole and also its crookedness made it very difficult to align the shallow anchor with the LVDT core. We had originally planned that the installation tool for the shallow anchor would fit the bore hole well enough to achieve this alignment, but due to both the size and crookedness of the hole, the installation tool did not serve this function. We aligned it visually as well as we could.

Once the anchors were set we tried to install the instrument. It was very difficult to insert the instrument fully into the borehole due to the crookedness of the hole and once inserted it was impossible to get the LVDT coil assembly started over the core. We removed the instrument to recheck alignment and then decided to attach a wooden tongue depressor to the coil assembly so that by rotating the instrument package we could more easily pick up the core. After several attempts we were successful in installing the instrument. We then tried to put the instrument into calibrate mode by shining a light on the communication electronics. The instrument would not respond to this command, so we removed the instrument from the borehole and took it above-ground where we disassembled it. We discovered that in the process of rotating the instrument during installation, we had rotated the end plug containing the communication electronics and had twisted off the wires that connect it to the rest of the instrument. These were repaired and the instrument was returned to the test location, installed successfully, and turned on. It operated satisfactorily until it was removed 68 hr later.

The instrument was returned to the laboratory in Richland and was disassembled. Inspection of the instrument components showed no signs of damage or moisture, but inspection of the paper tape showed signs of a

malfunction of the level 3 punch pin. Close examination of the punch pins indicated an interference problem between the level 3 punch pin and the level 2 pin anchor. Using a small pattern file, we increased the clearance between these two components so that they operated independently. Disregarding the errors introduced by the level 3 punch pin, the instrument operated for 68 hr and showed no rock movement (none was expected).

In preparation for the second test we devised some modifications designed to correct the difficulties encountered in the first test. These included increasing the thread tolerance and inside diameter of the shallow anchor to make removal of the installation tool easier and alignment of the anchor less critical; addition of a rubber washer to the outside diameter of the shallow anchor to form a seal between it and the borehole so that the Por-Rok would not run out; and fabrication of an extension for the shallow anchor installation tool which would center on the LVDT core and provide alignment of the shallow anchor.

The instrument system and modified equipment were returned to the underground test site and installation was started. The new borehole was 17 ft from the working face. Again, the hole was very crooked although we had no difficulty in installing either the deep or shallow anchor. However, when we started to install the instrument we again had difficulty in getting the LVDT coil assembly to slide over the core and again used a wooden tongue depressor taped to the end of the LVDT coil assembly to pick up the core. As in the first test, we were not able to start the barrel nut threads into the shallow anchor and it was left cross-threaded and jammed solid.

The instrument was removed from the borehole four days later and returned to our laboratory for disassembly and inspection. As before, there were no signs of damage or moisture and this time the paper tape was in good condition with no indication of malfunction in the punch head. During this test the instrument operated a total of 99.5 hr and indicated a displacement of 0.005 in.

Since we were still having trouble with alignment of the shallow anchor, we again modified the installation equipment to try and correct the problem. As we had no difficulties with the deep anchor installation, methods for it were not changed but we decided to make a major change in installation procedure for the shallow anchor. Instead of using an installation tool as we had previously, we decided to install the shallow anchor and the instrument at the same time. To do this, a rubber washer (dam) was installed at each end of the shallow anchor and a system was worked out with which we could inject Por-Rok into the cavity formed by the shallow anchor and attach rubber washers. With this method, the shallow anchor, the extension pipe and barrel nut, and the instrument could be assembled and then installed into the borehole, with the assembly being held in place with wooden wedges. Por-Rok could be pumped into the space between the shallow anchor and the borehole and left to harden. Once set, the wooden wedges could be removed and the instrument removed or adjusted as desired. This modified system was taken to the underground test site and installed in the third test hole. This test borehole was about 16 ft deep and located 4 ft from the working face. The borehole was as nearly vertical as possible. The installation using the modified equipment worked well and the instrument was turned on. This test was planned to last 12 days, but due to difficulty with access to the test site and scheduling problems the test actually lasted for 14 days. Both of our people returned to our laboratory in Richland for this period, but one of the U.S. Bureau of Mines people periodically checked the instrument during the test. About midway through the test period, he informed us that he thought the instrument was not operating normally. During several discussions by telephone over the next few days we were unable to decide whether or not the instrument was operating normally and decided to leave it in for the planned period. On schedule, we returned to the test site and removed the instrument. At the time of removal the instrument did not respond to light signals as it should have done. During the test, several excavation cycles were made. In our opinion these did not adversely affect either the anchors or the instrument. Disassembly of the instrument at our laboratory showed no mechanical damage, but from the punched paper tape it

was evident that the instrument had ceased recording after about 3 hr of installation. This failure does not coincide with the first excavation blast. We then tried to find the cause of the failure. In checking the batteries, most were completely discharged so we charged a new set of batteries and installed them in the instrument. We turned on the recorder and let it time out. When the print cycle started, the solenoids energized but the motor did not move. During this period we were able to check several wave forms at some key points on the circuit board. These checks revealed that the Motor Forward Drive Command from the digital logic circuitry and the proper voltages needed for motor operation were present.

This failure mode did explain the observed behavior of the instrument during the third test. With this type of failure the punch solenoids would remain energized until power was removed by an internal time out signal. This would cause the batteries to discharge at a rate at least 10 times normal. Obviously, the reported faulty operation of the recorder midway through the test period was due to low battery voltage.

During the check of the electronics circuit, one of two diodes in the motor drive circuit was bumped or touched which "healed" the problem. Further attempts to recreate the problem were in vain.

The problem while it occurred, however, was quite well defined and would be one of the following:

- Internal intermittent open diode, resistor, or SCR
- Cold solder joint
- Crack in the printed circuit board between components.

To eliminate all of the above possibilities, the six components in the circuit were replaced, the solder joints remade and solder flowed over the associated circuitry. Flexing of the printed circuit board did not cause reoccurrences of the problem.

To insure that the SCR's were not being marginally fired, the firing pulses were observed and compared with those specified by the manufacturer.

Gate voltage and current exceeded the minimum needed by 35%. Pulse duration is an order of magnitude greater than required and the motor always runs on the first of three or four pulses generated to start motor movement.

During installation of the self-contained system at the start of the third test, the anchors (both deep and shallow) that were installed for the first two tests were pulled using the anchor test system. Anchors used during the third test were pulled after the instrument was removed at the conclusion of the third test. The force required to remove the shallow anchors installed during the first two tests seems to be marginal. The deep anchor installed during the first test was marginal. Most of these marginal anchor installations can be attributed to either oversize holes or running water in the hole during installation. Where adequate amounts of Por-Rok were used, such as in the shallow anchor installation during test 3, results appear to be satisfactory. Loads used to pull the anchors are tabulated below:

- Hole No. 1

  The shallow anchor rotated while screwing in the extension pipes and first moved with a 300 lb pull; pulled out at 400 lb.

  The deep anchor rotated while screwing in the extension pipes and pulled out by hand.

- Hole No. 2

  The shallow anchor rotated with the extension pipes, and pulled out with a 5 to 20 lb pull.

  The deep anchor held solid with a 3500 lb pull.

- Hole No. 3

  The shallow anchor pulled loose with a 500 lb pull.

  The deep anchor held solid with a 2000 lb pull.

Although no significant data were collected during the third test, the entire test sequence is considered to be successful in that the instrument system survived the underground environment and that modification to the anchors and installation tools has resulted in a more reliable and usable system. Figures 12 through 19 show various activities during the underground evaluation.

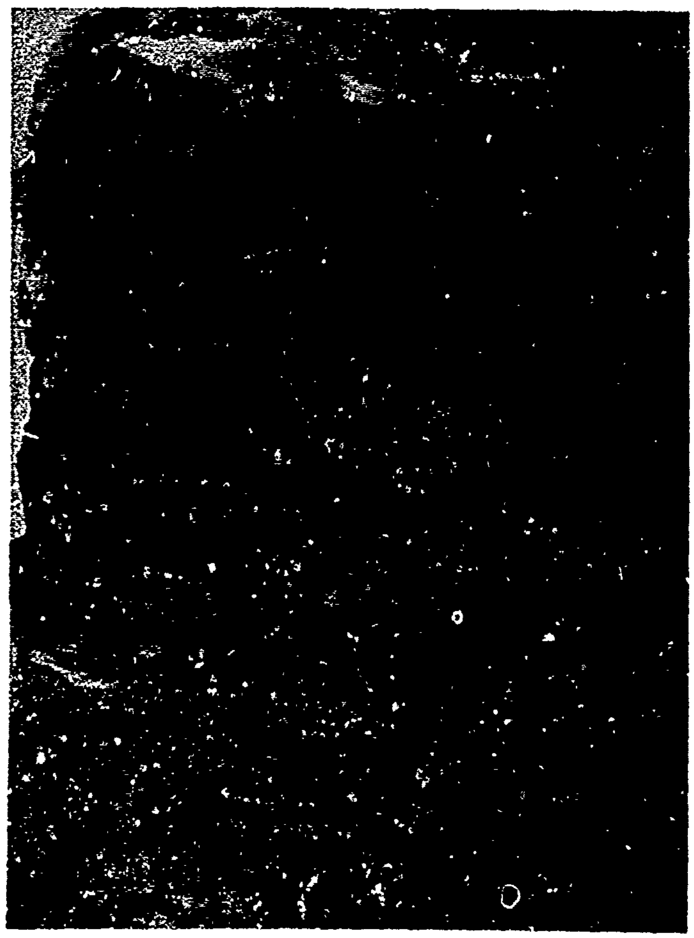

FIGURE 12. Location of First Underground Test (Typical of Each Test)

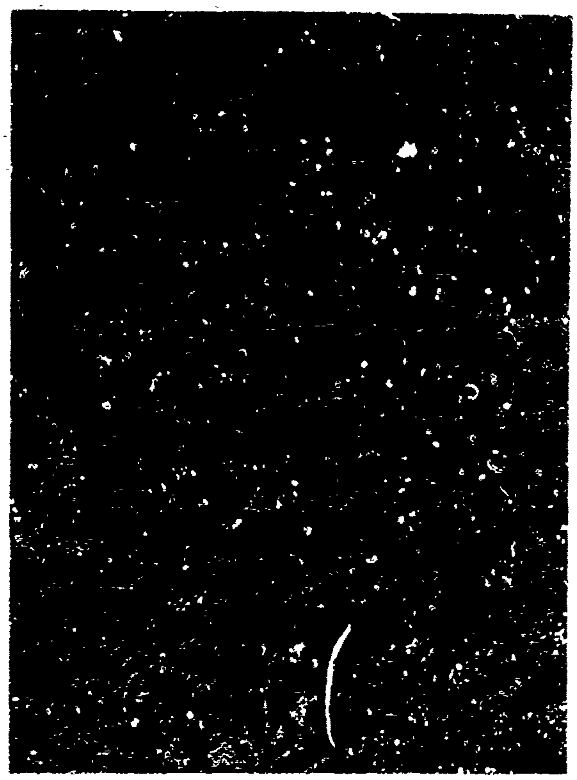

FIGURE 13. Self-Contained System Ready for Installation Underground. The instrument appears on middle right. Shown in the lower left foreground is the deep anchor on its extension.

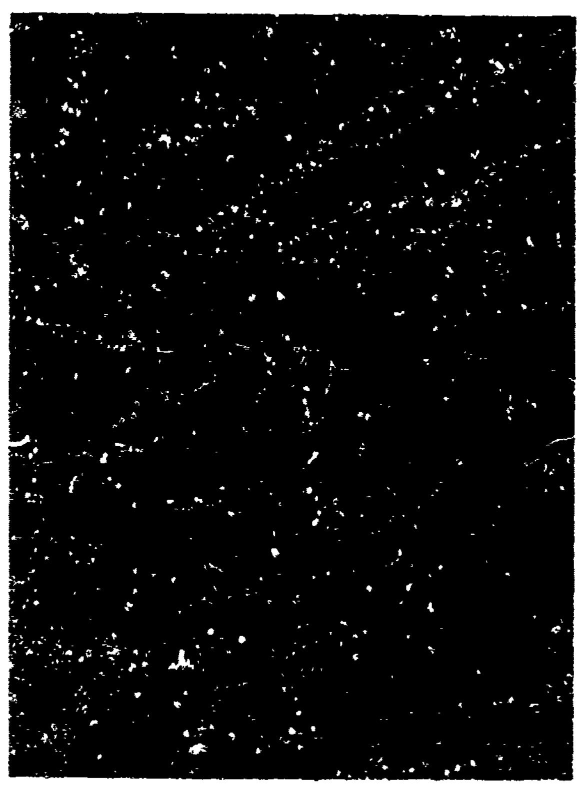

FIGURE 14. Installation Tool in Place in the Borehole

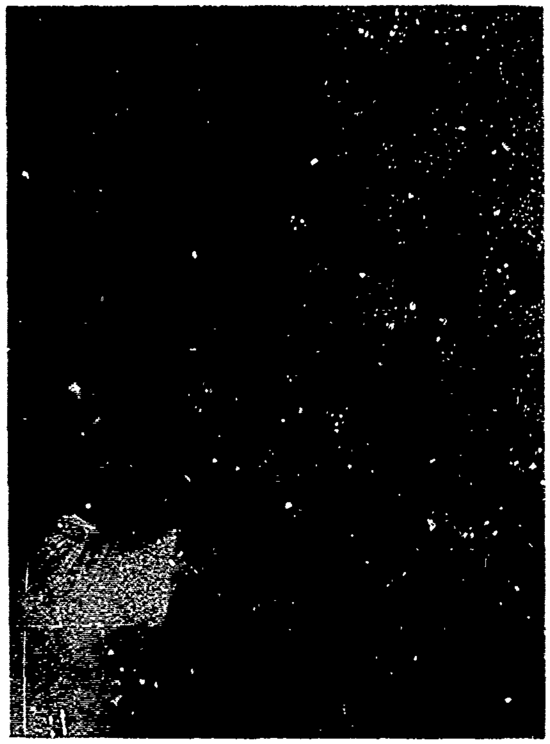

FIGURE 15. A Miners Lamp Being Used to Turn On the Self-Contained Instrument

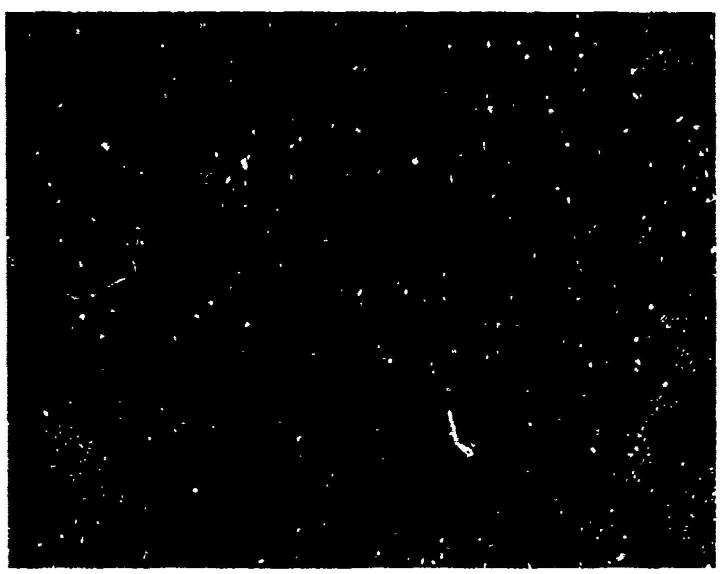

FIGURE 16. Zeroing the Installed Instrument Using the Special Wrenches While Observing the LED's Through the Center Wrench

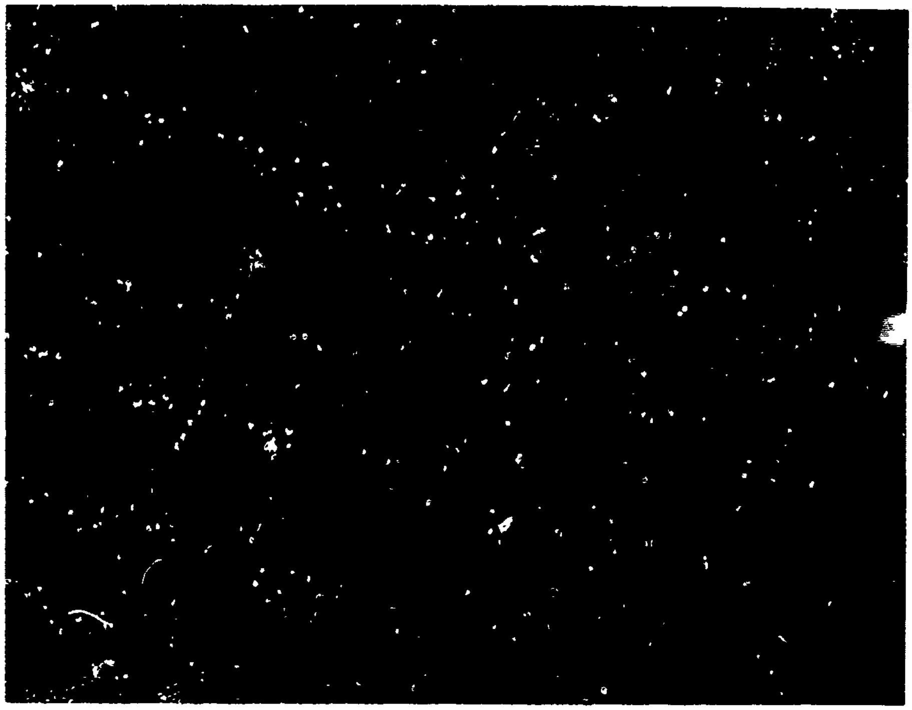

FIGURE 17. Modified Shallow Anchor Used During the Third Test. Note the hoses used to inject the Por-Rok.

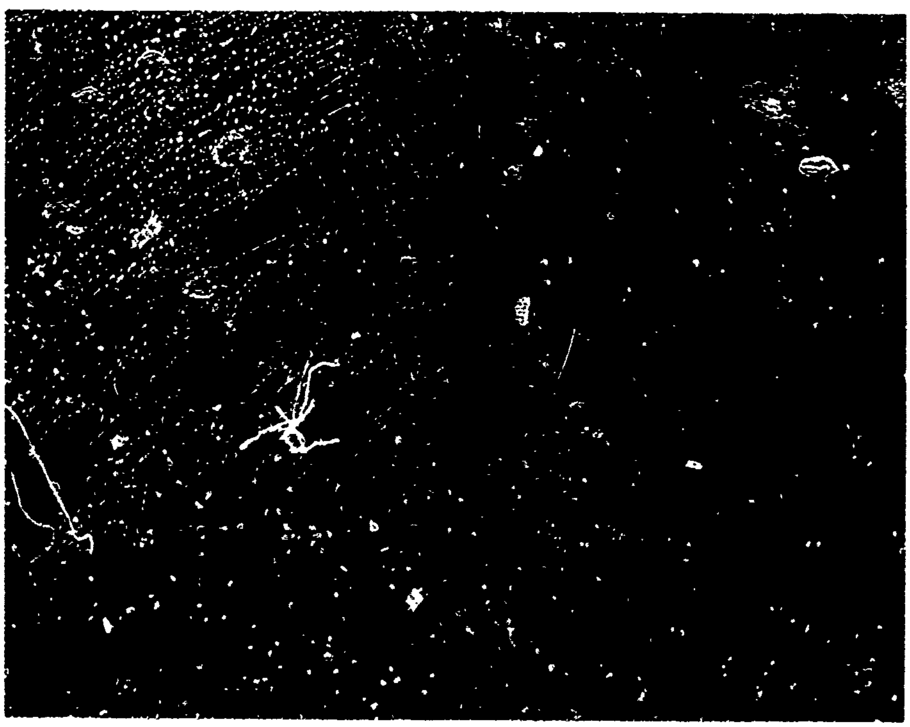

FIGURE 18. Wedges Used to Hold the Instrument Package and Shallow Anchor in Place While the Por-Rok is Curing

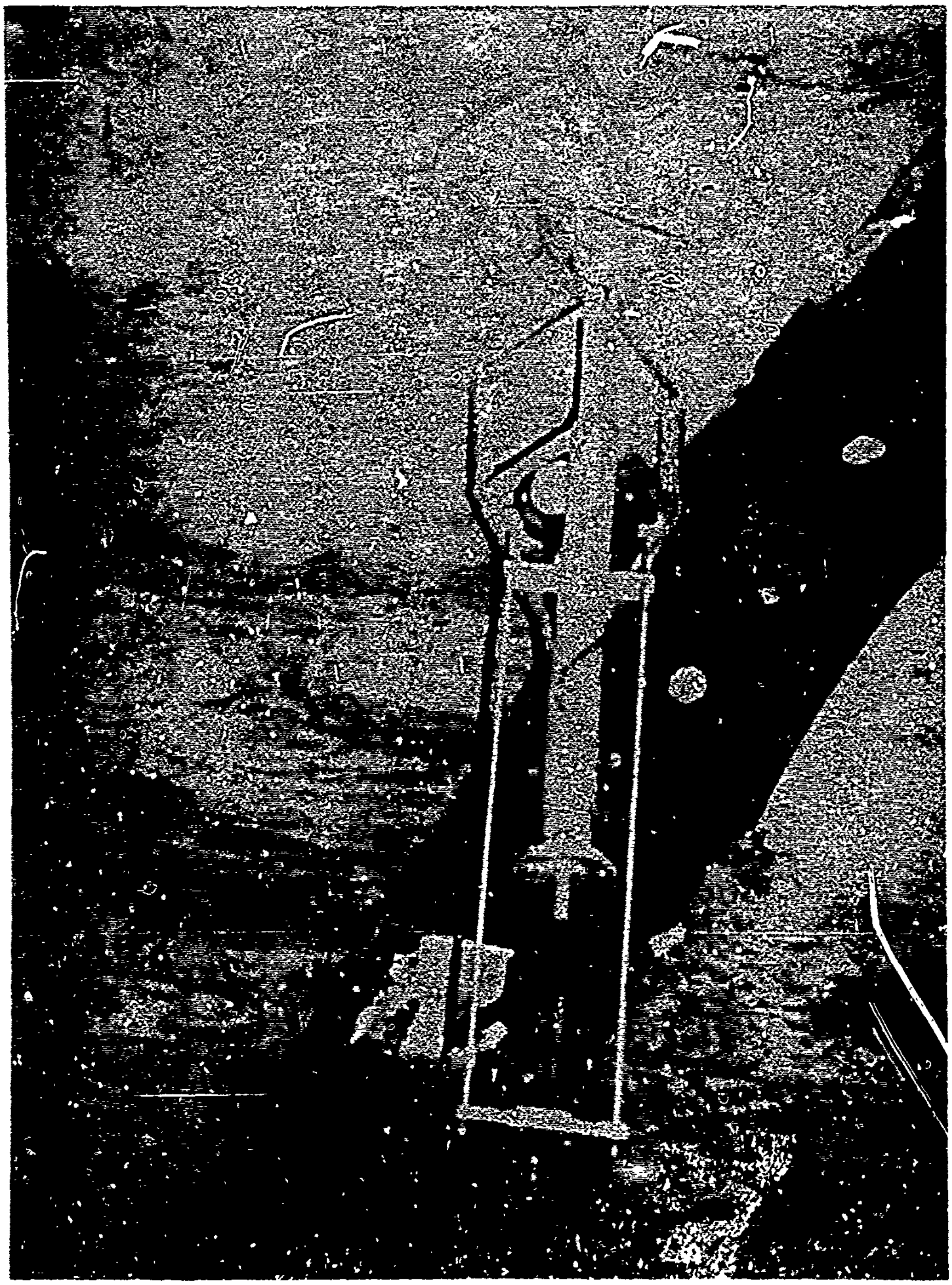

FIGURE 19. Anchor Pull Test Stand Being Used to Pull the Anchors After the Third Test

LASER SYSTEM

During the final month of the previous contract year, evaluation of the stepping motor - ball screw driven scanner system showed that device capable of producing reproducibility in beam position of 0.015 in. over 300 ft. Tests in an environmental chamber showed the concept to be operable in a dusty environment as long as particle density was not sufficient to block the beam.

Work during this year has been directed toward prototype design and assembly. Design decisions were based on results of experiments to determine applicability and practicality of concepts proposed for each major component. These experiments led to the designs described below.

CHOPPER OR SPATIAL MODULATOR

Detailed requirements on the chopper are determined by the electronic technique used to identify and record signals. At a minimum, however, the chopper must produce two mutually orthogonal scans of the transmitted beam.

Laboratory tests were conducted on a device which used Dove prisms to produce orthogonality of the scans. The two beams produced by a rotating slotted cylinder were passed through Dove prisms, one of which was rotated 45° with respect to the other. This arrangement produced an angle of 90° between shadows cast in the beam. Alignment of the system was extremely difficult, additional losses in transmitted intensity were suffered because of the two interfaces and one reflection in each prism, and the presence of the prisms increased mechanical stability requirements on the system.

Other arrangements employing two motors and two wheels were briefly investigated, but the single motor requirement of a cylindrical chopper is strong motivation for choosing that concept. The selected chopper design is shown in Figure 20.

Light from the laser enters the rotating cylinder on its axis. A 50% beam splitter set at 45° directs half the intensity horizontally to a

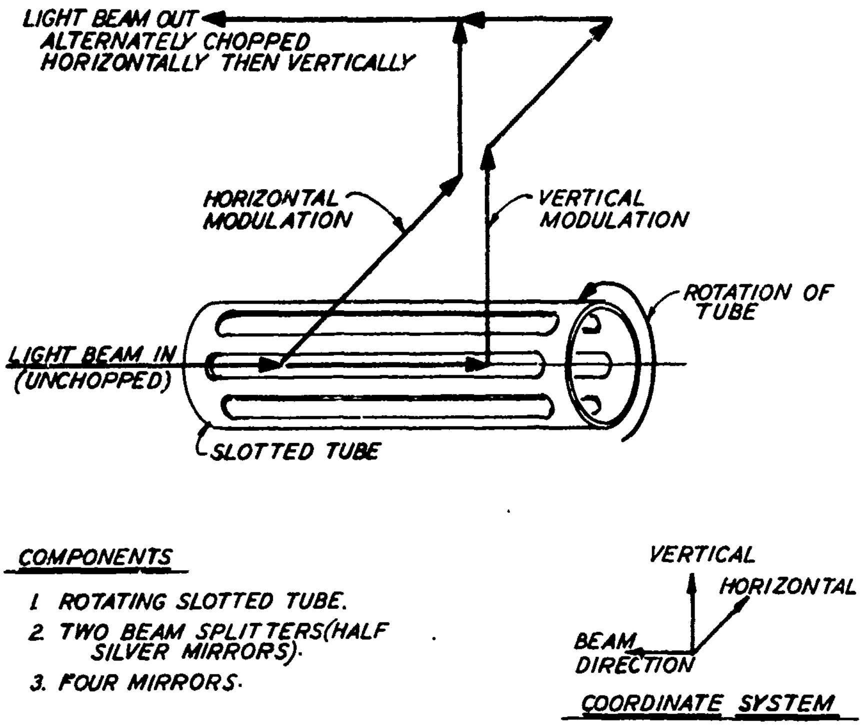

FIGURE 20. Spatial Chopper

mirror, set at 45° with respect to the vertical, which reflects the chopped beam vertically to a splitter that directs the beam parallel to and in the opposite direction of the laser output. This beam carries the horizontal modulation. Vertical modulation is provided by passing the remaining 50% of the beam through the chopper on a vertical path and using two more mirrors to superimpose the vertically modulated beam with that carrying the horizontal modulation, as shown in Figure 20.

SIGNAL IDENTIFICATION

Previous work assumed that a two-frequency spatial modulation system would suffice to allow identification of vertical and horizontal signals. Two filters from United Transformer Company were investigated, an HPM 500 high-pass minifilter with low frequency cutoff at 500 Hz, and an LPM 500,

low-pass minifilter with high frequency cutoff at 500 Hz. Both filters exhibited 10,000 Ω input and output impedance, and a fall-off at band edge of 40 dB per octave. Laboratory work showed that, with frequencies of 300 and 600 Hz, available low-pass and high-pass filters did not possess sufficiently sharp cut-off to guarantee separation of the two frequencies.

A greater frequency spread between the two signals would have permitted this approach to be followed, but the necessary ratio of approximately 5 to 1 would have resulted in great disparity in data rates between vertical and horizontal modulation. Because of these difficulties the final device will operate with only one frequency. Time gating will be used to identify signals.

The single frequency concept can best be understood by describing the chopper as a generator of pulses at a desired pulse repetition frequency (PRF) rather than a device for generating a signal at a given frequency. Each pulse can be thought of as a probe used to find the target position.

Two position measurements will be made with each pulse; one triggered by the rise, the other by the fall of the reference pulse. The derivative of the reference and target pulses will be used to start and stop, respectively, an oscillator which, when coupled with a counter, will serve as a clock. If the velocity of the chopper blade is v, the shadow cast by the chopper will propagate across the transmitted beam with velocity mv, where m is the magnification factor in the second collimator. Thus, the position of the target with respect to the beam edge will be $\xi = mv\tau$, τ being the time interval observed on the clock. Distinguishing between vertical and horizontal signals will be performed by controlling the time interval during which acceptable data will be recorded. A schematic representation of the beam cross section and signals generated by the chopper is shown in Figure 21.

Signals in Figure 21 denoted V_r (H_r) represent reference pulses generated by the vertical (horizontal) pass of the chopper blade edge through the beam. Since alternate pulses from the chopper carry different directions

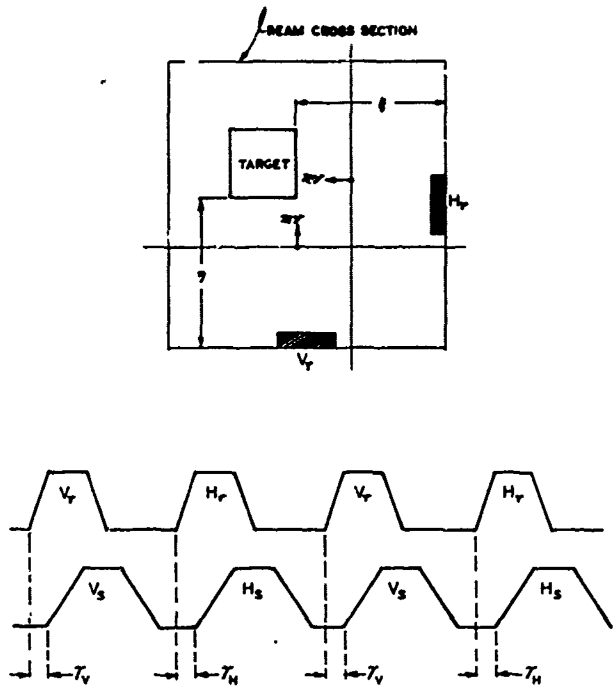

FIGURE 21. Transmitted Beam and Generated Signal. Target position is determined by $\xi = mv\tau_h$, $\eta = mv\tau_v$.

of modulation, two eventualities must be guarded against so that the data will be meaningful. First, if the target is close to the beam edge, poor definition caused by diffraction effects can contribute to error. Consequently, signals from the target which rise within 30 μsec of the reference signal rise will not be accepted as good data. This corresponds to a target position of 0.055 in. from the beam edge. In order to avoid confusion between vertical and horizontal signals, overlap must be avoided. That is, data will not be accepted if, for example, the horizontal signal rises before the preceding vertical signal falls to zero. Under the present design, target motion greater than 1.0 in. from the beam edge in either the vertical or horizontal direction will cause rejection of the data. The electronics necessary to operate the system will be described later.

BEAM SCANNING SYSTEM

At the beginning of this contract year we were requested to consider means for incorporating capability for a full 360° horizontal scan in the prototype system. To this end, a worm gear driven beam scanner system was fabricated for evaluation. Such a scanning system would be applicable to a 360° horizontal scan, and could be packaged in a compact form for field use. The stepper motor used in this evaluation was a Slo-Syn SS25-1002 with a 1.8° rotation per step and a quoted reproducibility of 3%, or 1 part in 33. The gear ratio of 100 to 1 provided mirror motion of 0.018° per step. It is not planned to use this motor in the final prototype, but it is sufficient for evaluation.

Vertical

Tests were performed in a simple vertical scanner over a 10-meter path. As in previous tests of this nature, a phase meter was used in the measurement of reproducibility and stability. One test consisted of 19 scans over 4 steps up and 3 steps down, another test consisted of 11 scans over 1 step up and 1 step down. The data are shown in Table 1. A 54- min stability test yielded total motion of 0.00376 in. while a 104 min test gave a total deviation of 0.00846 in.

TABLE 1. Test Data

19-Scan Test

Step No.	Avg Step Lgth, in.	Standard Deviation	Reproducibility
1 up	0.2669	0.01927	1/33
2 up	0.2707	0.00340	1/80
3 up	0.2165	0.00029	1/747
4 up	0.2093	0.00253	1/83
1 down	0.2026	0.00223	1/91
2 down	0.2434	0.00203	1/120
3 down	0.3366	0.00445	1/76
11-Scan Test			
1 up	0.2465	0.00300	1/82
1 down	0.2580	0.00184	1/140

Except for the first step in the 19-scan test, the reproducibility of this approach is near 1 part in 100 with an average of 1 part in 175 even with the low reproducibility of the stepper motor employed. For comparison purposes, the previously developed scanner system with the specially selected motor gives average reproducibility of 1 part in 150. The worm gear driven device gives comparable reproducibility. These results motivated the design shown in Figure 22 for the scanning system.

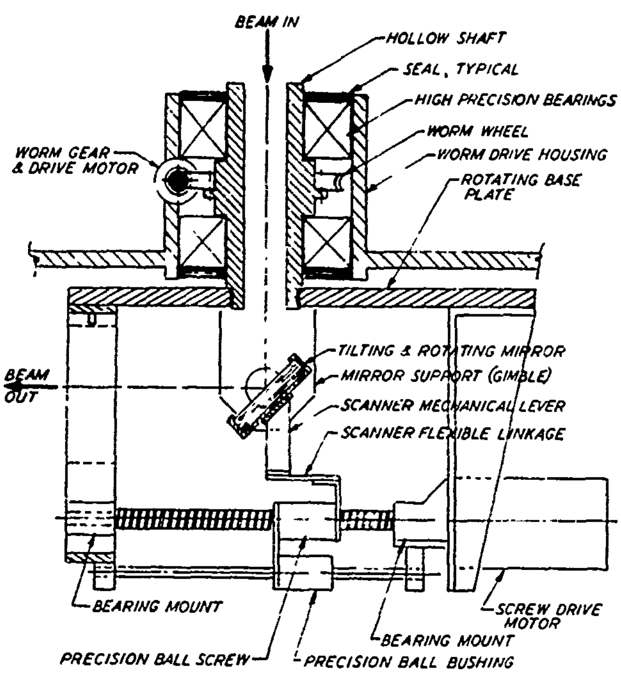

FIGURE 22. Horizontal and Vertical Scanner Assembly

The vertical scanner is the same used in the previous evaluated one-axis device. It utilizes a stepper motor, a ball screw and a mechanical linkage to rotate a mirror, thus producing a vertical scan. Mounting brackets originally used have been replaced due to a change in orientation of the device. The light beam comes vertically downward striking the mirror and reflecting in the direction to be scanned.

Horizontal

Horizontal scanning is provided by rotation of the entire vertical scan and mirror mount system. A special design worm gear speed reducer driven by a stepper motor will rotate a hollow shaft attached to the vertical scan assembly. The light beam enters the hollow shaft vertically and proceeds downward to contact the scanner mirror. From there, it leaves the instrument essentially in a horizontal direction passing down a tunnel to contact a target, returning to be monitored. The use of the hollow shaft which rotates to produce the horizontal scan allows for full rotation unobstructed viewing. This arrangement also produces a quite compact integrated scanning system.

The worm gear reducer consists of a large diameter worm wheel mounted to the hollow shaft meshed to a worm gear which is affixed to the housing. Large preloaded angular contact bearings support the hollow shaft. The worm gear is mounted on a long slender drive shaft coupled to a stepper motor. This small shaft is supported by small angular contact bearings in pairs at the ends of the shaft. The worm wheel and worm gear will be mounted in light interference to reduce the possibility of scanning error. The gear system is a four-thread type made of hardened steel and bronze and produces a 45:1 reduction. The bearings and gears are all sealed in a housing and properly lubricated. A torsion spring will be attached between the housing and the rotating member, as required, in order to eliminate all gearing backlash.

PROTOTYPE SYSTEM

With the foregoing work as a basis for design decisions, the system shown in Figure 23 is now under construction.

The system is organized to fit on a 6 in. by 3 in. by 3/16 in. aluminum box section extrusion approximately 3 ft long. Figure 23 shows the system layout exclusive of electronics and power supplies which are expected to be housed separately and connected with an umbilical. The equipment shown here is expected to fit overall dimensions of 13 in. high by 16 in. wide by 38 in. long and weigh between 25 and 50 lb.

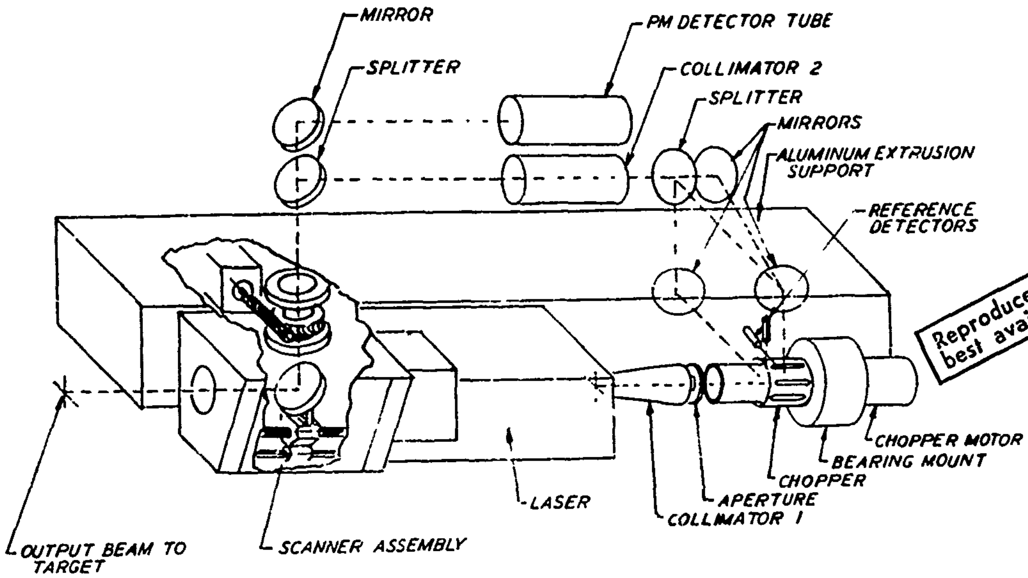

FIGURE 23. Prototype Mechanical and Optical Design of the Laser System

The laser (helium neon, 5 MW) sends a beam horizontal from its position mounted on the side of the aluminum extrusion. The beam is expanded to 0.3 in. diameter by collimator No. 1 and passes through a square aperture. The beam then enters a mirror system which splits the beam into two parts, one going horizontal toward the center of the aluminum structure and the other going vertically upward. A cylinder with lengthwise slots encircles the mirror splitting system and cuts (chops) the two beams as it rotates at 3600 rpm. A mirror near the center of the aluminum box section diverts the horizontal beam vertical and a mirror mounted above the cylindrical chopper diverts the vertical beam horizontal. These two beams intercept at a two-mirror arrangement which recombines the two beams into one. The resulting beam is now positioned above the aluminum structure and directed down its length in the opposite direction from when it entered the chopper. The beam now has alternately traveling shadows (horizontal, then vertical, then horizontal, etc.), a square shape and is collimated (parallel). This beam passes through collimator No. 2 to be expanded by five times with an overall beam width and height of approximately 1 1/4 in. From here, it

intercepts a large beam splitter and is deflected vertically downward. Next, the beam strikes the scanner mirror and is deflected approximately horizontal in the scanning direction. Scans of about 3/4 in. at 300 ft up or down and right and left per step of the stepper motor are achieved.

Operationally, the laser and the spatial chopper operate continuously with the horizontal and vertical steppers providing a controlled scan of a predetermined window (say 5° vertical by 10° horizontal). Targets located up to 300 ft from the instrument will reflect light back to the instrument. This low intensity return beam intercepts the scanner mirror, is deflected upward through a splitter mirror, and then reflected to enter a photomultiplier tube for detection.

When the light detector receives a return signal, the scan is stopped and locked onto the target. The time delay between reference and return signals locates the position of the target relative to a predetermined "origin" located within the light beam. Measurement is made by comparing the time delay between a signal from a reference light detector (located in the chopper housing) and a signal returned from the target to the photomultiplier tube.

This time delay, plus the data concerning which vertical and horizontal step the instrument is positioned to, will give quite an accurate measure of the target position (vertical and horizontal). Monitoring this position for 50 targets over a considerable time span will produce data on motion (expansion or dilation as well as nonsymmetrical) movement of an underground opening.

PROTOTYPE ELECTRONICS

A basic block diagram of the complete prototype system is shown in Figure 24. The beam position sequencing logic is the control center of the electronics system. This package contains necessary control circuits for automatic operation of the two Respon-Syn HDM-150-800-4 stepping motors which drive the beam scanner. A logic flow diagram for the system is shown in Figure 25.

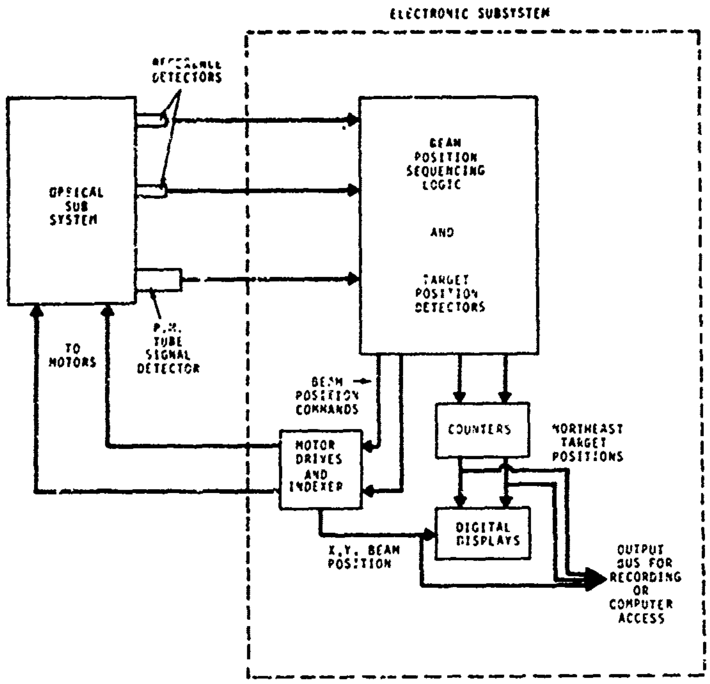

FIGURE 24. Block Diagram of Laser Dislocation System

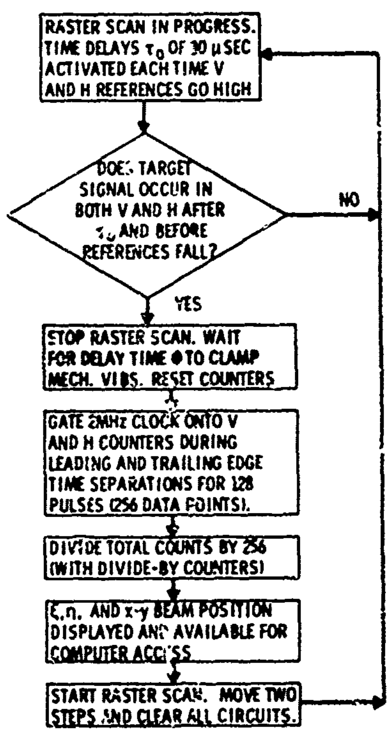

FIGURE 25. Logic Flow Diagram for the Laser System

Under operation the beam will describe a raster scan covering the target field. The vertical scanner will complete one sweep through the range (e.g., 5°), the horizontal scanner will move one step of its range, and the vertical scanner will again sweep out its range. A raster scanner formed in this way will require most motion on the ball-screw driven scanner, thus minimizing wear on the worm-wheel set. The scan will continue until returning signals can be identified unambiguously. This test is performed to avoid edge effects and to prevent confusion between vertical and horizontal references as discussed under the chopper design section. When returning signals meet crite ia established to identify sound data, the raster scan will be stopped and target position data accumulated.

A timing diagram for the data acquisition mode is shown in Figure 26. The reference pulses are obtained from optical reflectance transducers consisting of an LED (light emitting diode) and a photo transistor mounted in a 1/4 in. square epoxy package. They are positioned over the chopper so that chopper slots uncover a mirror, resulting in a reference signal coincident with the appearance of light in the interrogation beam. The elapsed time between the leading edges of the reference pulse and the target signal provides a measure of target position within the beam, provided that chopper speed is known and constant.

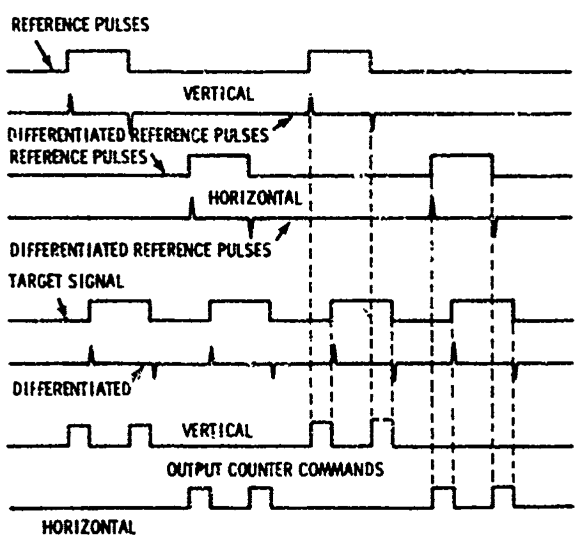

FIGURE 26. Data Acquisition Waveforms for the Laser System

To provide greater measurement accuracy, both the leading and trailing edge time differences are measured a total of 128 times for each stop on a target, and an average quantity is delivered to the output devices. Data averaging and output are accomplished by gating a high-frequency clock into a pair of divide-by-256 counters during the measurement intervals. These counter gating commands are shown in relationship to electro-optic signals in Figure 26. The target position information (ξ,η) is available in binary coded decimals from the counter outputs until the next target is incident in the beam, and the X,Y beam position will be clocked into a storage register during the data acquisition stop.

Differentiation of the electro-optical signals is used so that leading and trailing edges can be distinguished with diode-steering techniques. The differentiation is performed with integrated operational amplifiers and the balance of the completed digital circuitry consists of 24 TTL (transistor-transistor logic) packages operating from a 5-V supply.

ACKNOWLEDGEMENTS

We wish to acknowledge the help given during the field testing of the self-contained system by Hecla Mining Company and the U.S. Bureau of Mines, Spokane Mining Research Center. Specific thanks to Art Brown for arranging the test site; to Gordon Pew for assisting during the tests; and to Mike Beus for assistance during the tests and for photographs taken underground.